Multimodal Response Retina-Inspired Memristor for Reconfigurable Optoelectronic Computing

Introduction

Biological visual systems can efficiently accomplish optical signal capture, preliminary information processing, memory formation, and dynamic state resetting in complex environments. Compared with conventional artificial vision systems, biological vision is distinguished by its massively parallel information-processing architecture and the intimate coupling among sensing, storage, and computation. For instance, low-light-adapted organisms such as deep-sea octopuses are capable of highly sensitive visual perception under dim illumination. Their visual nervous systems not only respond rapidly to weak optical stimuli, but also regulate synaptic weights to enable transient retention and dynamic adaptation to environmental information. Such a perception–memory-integrated neuromodulatory mechanism provides important inspiration for the development of low-power neuromorphic vision hardware.

In recent years, optoelectronic synaptic devices have been regarded as essential building blocks for neuromorphic vision systems. These devices can directly convert optical signals into postsynaptic-current-like electrical responses, thereby enabling preliminary information encoding at the device level. Compared with conventional physically separated architectures consisting of photodetectors, memory units, and processors, optoelectronic synaptic devices can substantially reduce data transfer and energy consumption. Nevertheless, existing optoelectronic synaptic devices still face several critical challenges. First, many devices rely on an external bias for operation, which increases system-level power consumption. Second, optical writing and electrical erasing typically require different external stimuli, leading to increased peripheral circuit complexity. Third, although some devices can realize photoresponse and synaptic plasticity, it remains difficult to simultaneously integrate self-powered response, all-optical modulation, and information resetting within a single device.

Finally, array-level optical writing, erasing, and reconfigurable imaging capabilities still require further improvement.

Perovskite quantum dots have attracted extensive attention in photodetectors, memristors, and neuromorphic devices owing to their high absorption coefficients, tunable bandgaps, long carrier diffusion lengths, and excellent photoelectric conversion capability. In particular, by engineering the quantum dot size, composition, and interfacial structure, the generation, transport, trapping, and recombination of charge carriers can be effectively regulated, providing a versatile material platform for constructing multimodal optoelectronic synapses. In addition, the coupling between perovskite quantum dots and hole-transport layers, metal electrodes, or oxide interfaces can induce tunable energy-band bending and interfacial barriers, enabling reconfigurable photoelectric responses under different biases and illumination wavelengths.

In this work, we design a reconfigurable optoelectronic memristive synaptic device based on a perovskite quantum-dot heterostructure. Through rational device architecture and interfacial energy-band engineering, three key functions are integrated into a single platform. First, the device generates a self-powered photoresponse under zero bias, enabling low-power optical sensing. Second, under negative bias, all-optical synaptic modulation is achieved through 660 nm red-light writing and 395 nm ultraviolet-light erasing. Third, under positive bias, information resetting is realized, thereby suppressing the influence of residual historical states on subsequent sensing processes. Furthermore, we construct an arrayed device platform and demonstrate image writing, erasing, retention, and reconfigurable display capabilities. This work not only highlights the potential of perovskite quantum dots for neuromorphic vision hardware, but also provides a new strategy for developing self-powered, all-optically controlled, and resettable sensory-memory-computing integrated visual systems.

Result

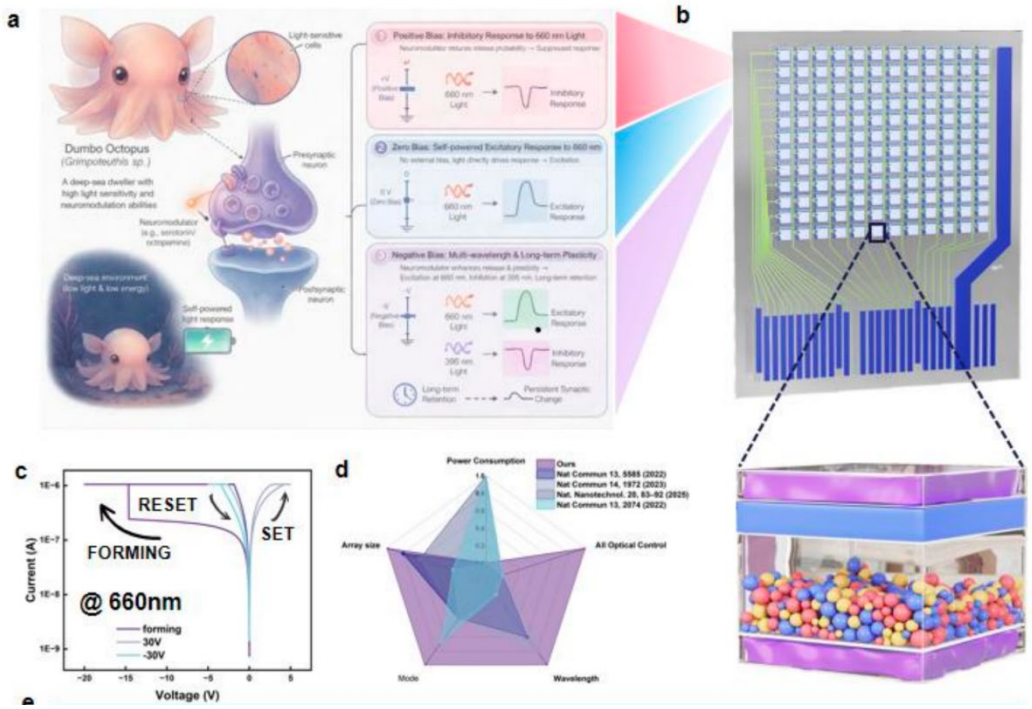
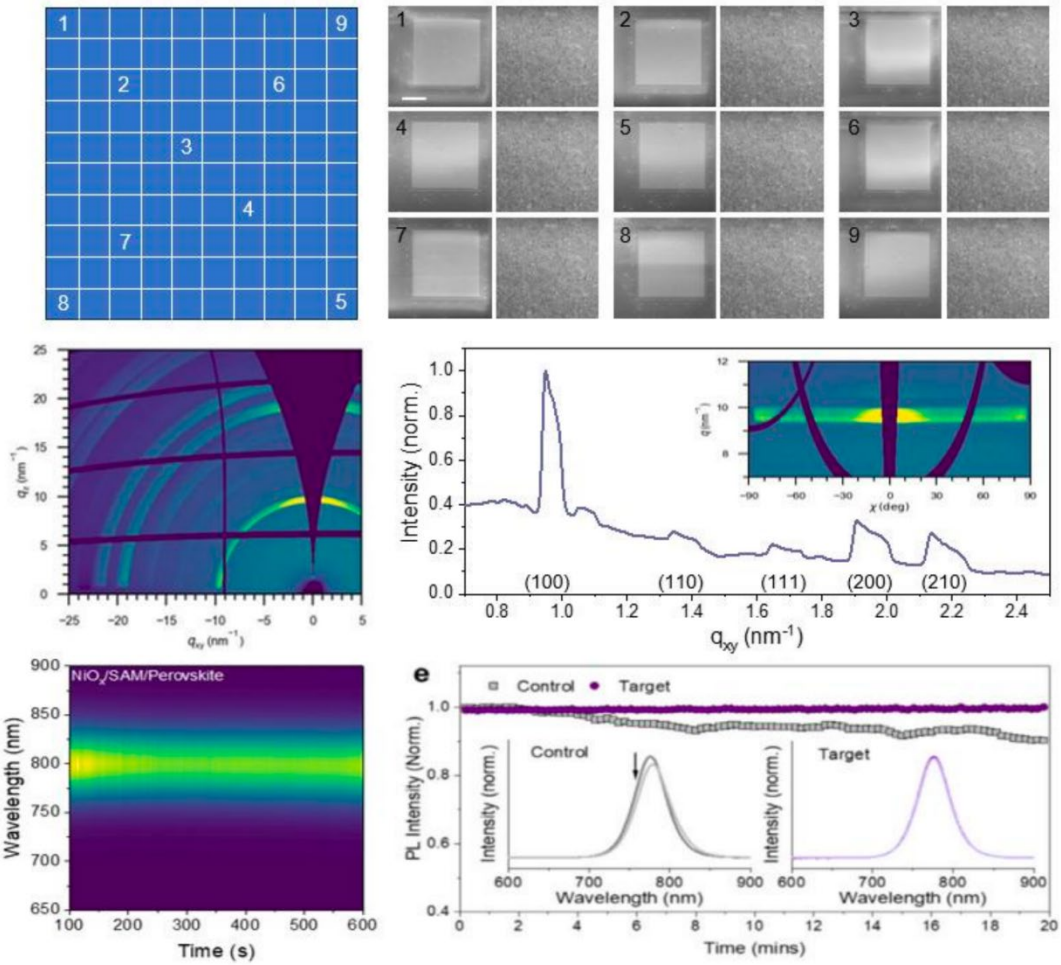


Figure 1a illustrates the bioinspired origin of the device design. Deep-sea octopuses are capable of highly sensitive visual perception under low-light conditions. Their visual systems rely not only on the direct response of photoreceptive cells to optical signals, but also on the dynamic regulation of optical stimuli by synaptic networks. Inspired by this biological mechanism, we constructed a perovskite quantum-dot-based optoelectronic memristive synaptic device that can simultaneously realize optical sensing, optical modulation, and information resetting.

The core device architecture consists of a top electrode, a functional perovskite quantum dot layer, an interfacial modulation layer, and a bottom electrode. As schematically shown in Figure 1b, the perovskite quantum dot layer is sandwiched between the top and bottom electrodes and forms a heterostructure with the interfacial layer. Under illumination, this heterostructure can efficiently generate photogenerated electron–hole pairs, while the interfacial barrier and defect states further regulate carrier separation, trapping, and release. Therefore, the conductance state of the device is determined not only by the applied voltage, but also by the illumination wavelength, optical power density, pulse duration, and previous stimulation history.

The core operating modes of the device can be classified into three categories. First, under zero-bias conditions, the device exhibits a pronounced self-powered response to 660 nm illumination. This indicates that optical signal detection can be achieved without an external power supply, making the device suitable for low-power visual perception. Second, under negative bias, 660 nm light induces an increase in device conductance, corresponding to an excitatory synaptic response, whereas 395 nm light decreases the conductance or restores it toward the initial state, corresponding to inhibitory modulation or optical erasing. This mode enables writing and erasing to be accomplished under purely optical control. Third, under positive bias, the device exhibits an information-resetting function, by which the conductance state generated by previous optical stimulation can be rapidly restored to the baseline state, thereby improving the repeatability and stability of the visual system during continuous operation.

This three-mode modulation mechanism endows a single device with integrated functions of “optical sensing–optical memory–optical erasing–electrical resetting.” Unlike conventional photodetectors, the device does not merely output transient photocurrent signals, but can convert the history of optical stimulation into a retainable conductance state. Unlike conventional electrically driven memristors, the device can directly modulate synaptic weights using optical signals, thereby significantly reducing peripheral circuit complexity and providing a compact device-level platform for neuromorphic visual sensing and memory.



To verify the optoelectronic functionality and structural stability of the perovskite quantum dot film, we systematically characterized its morphology, crystallinity, and optical properties. Figure 2 presents the structural and spectroscopic characterization results of the film and the corresponding devices.

First, optical microscopy and film morphology characterization reveal that the perovskite quantum dot film exhibits relatively uniform coverage and a continuous surface morphology. The comparable film quality across different pixels within the array region provides a solid basis for achieving good device-to-device uniformity in large-area arrays. The enlarged images in Figure 2 further confirm the good spatial uniformity of the functional layer within the device region, without obvious large-area cracks or pinholes.

Second, grazing-incidence wide-angle X-ray scattering (GIWAXS), or related X-ray scattering characterization, demonstrates that the perovskite quantum dot film possesses distinct crystalline diffraction features. Characteristic diffraction signals associated with the perovskite lattice can be observed, indicating that the quantum dot film retains a well-defined crystalline structure after film formation. The corresponding one-dimensional integrated profile exhibits multiple characteristic peaks, including diffraction peaks assigned to specific crystal planes, further confirming the presence of a well-defined crystalline phase. Such ordered crystallinity is beneficial for the generation and transport of photogenerated carriers, while also providing a stable material foundation for interfacial charge modulation.

Third, photoluminescence (PL) spectroscopy shows that the target sample exhibits a pronounced emission peak in the near-red spectral region and demonstrates more stable emission intensity compared with the control sample. As shown in Figure 2e, the normalized PL intensity of the target sample remains relatively stable during the measurement, whereas the control sample shows a certain degree of degradation. This result suggests that, after interfacial or compositional modulation, nonradiative recombination in the perovskite quantum dot film is effectively suppressed, leading to improved photogenerated carrier stability. A stable optical response is particularly important for optoelectronic synaptic devices, as it directly affects the response consistency and state retention capability under repeated optical stimulation.

In addition, the time-dependent spectroscopic results in Figure 2 indicate that the device maintains a clear emission feature during prolonged measurement, suggesting good operational stability of the perovskite quantum dot layer. This provides a reliable material basis for subsequent demonstrations of multipulse synaptic modulation, array-

level imaging, and repeated optical writing/erasing operations.

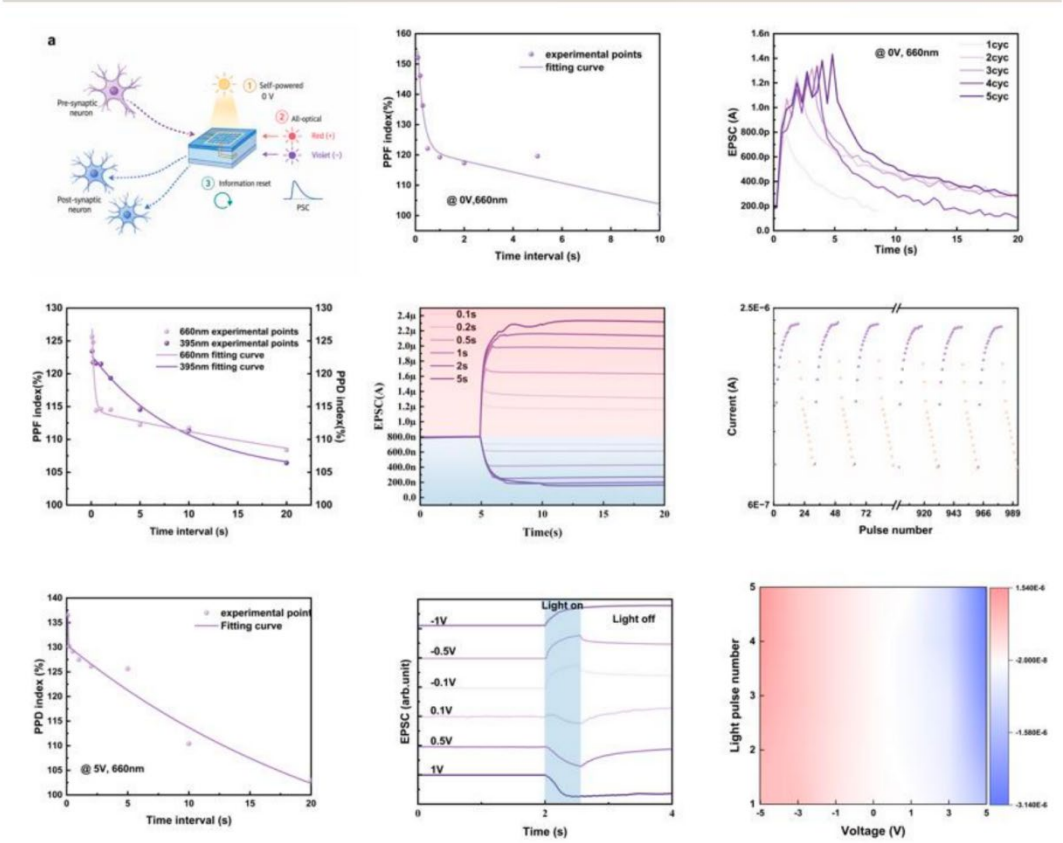


Figure 3 presents the electrical and optoelectronic synaptic characteristics of an individual perovskite quantum-dot memristive synaptic device. First, the device exhibits typical memristive switching behavior during voltage sweeping. Under 660 nm illumination, the I–V characteristics display distinct SET and RESET processes, indicating that light irradiation can significantly modulate the internal conductance state of the device. After the forming process, reproducible switching between high- and low-resistance states can be achieved during subsequent voltage sweeps. This light-assisted memristive behavior suggests that photogenerated carriers participate in the formation of conductive pathways, modulation of interfacial barriers, and/or filling of defect states.

Under 0 V bias, the device shows a pronounced self-powered response to 660 nm optical stimulation. The EPSC curves in Figure 3 reveal that light irradiation can induce a postsynaptic-current-like response even in the absence of an external bias. This

phenomenon can be attributed to the built-in electric field formed within the device heterostructure. Upon illumination, the perovskite quantum dots absorb photons and generate electron–hole pairs, while the built-in electric field promotes carrier separation, thereby producing a photocurrent in the external circuit. Since this process does not require an applied voltage, it is beneficial for reducing the static power consumption of visual sensing systems.

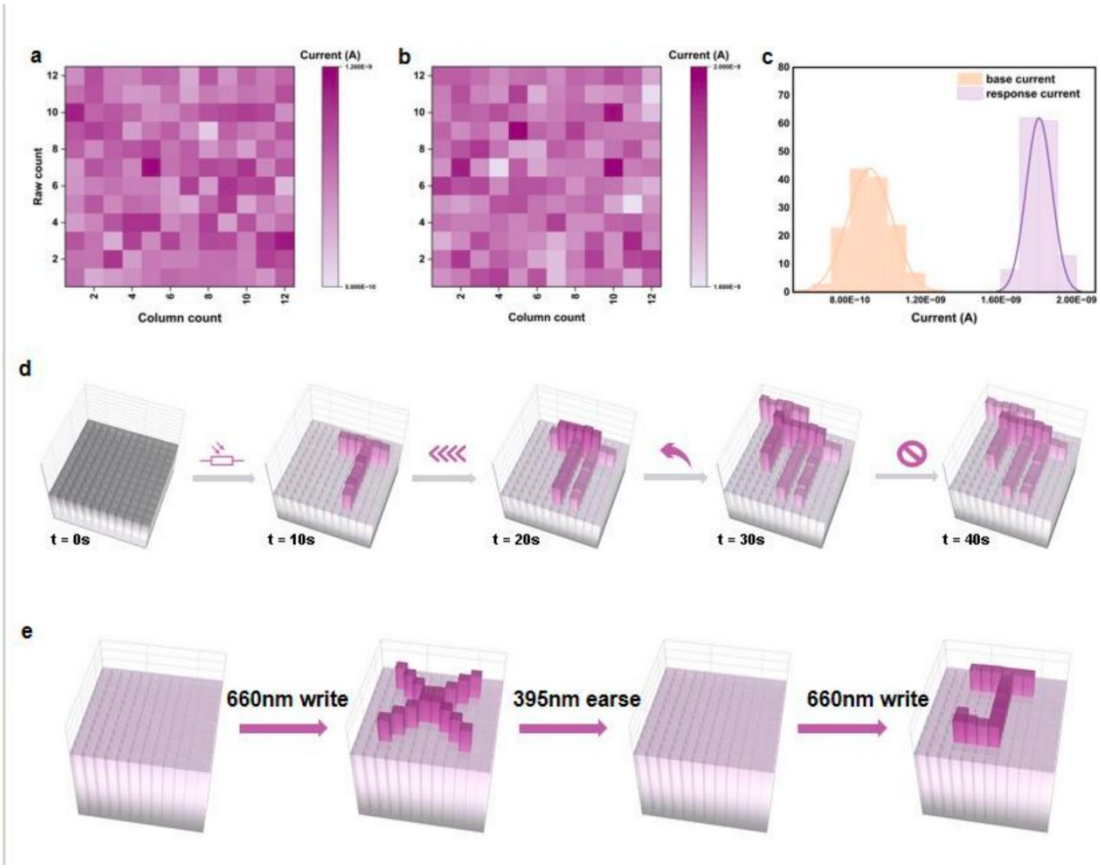
Furthermore, the device exhibits pronounced time-dependent synaptic plasticity. By tuning the interval between paired optical pulses, the paired-pulse facilitation index gradually decreases as the pulse interval increases, consistent with the decay behavior of short-term plasticity in biological synapses. This behavior indicates that when the intermediate state induced by the first optical pulse has not fully relaxed, the second pulse can trigger a stronger response, resulting in temporal integration analogous to the residual calcium effect in biological synapses. For neuromorphic vision, such short-term memory is advantageous for extracting temporally correlated information from dynamic optical stimuli.

The EPSC response of the device also shows a clear dependence on optical pulse duration. Longer light pulses induce stronger current responses and longer retention times, indicating that the optical stimulation energy can effectively regulate the carrier trapping depth and conductance state within the device. Meanwhile, multipulse stimulation experiments reveal a gradual accumulation of device current with increasing pulse number, resembling long-term potentiation behavior. These results demonstrate that the device can not only respond to individual optical stimuli, but also integrate and memorize consecutive optical inputs.

Notably, the device exhibits switchable excitatory and inhibitory responses under different bias conditions. Under negative bias, 660 nm light enhances the device conductance and generates an excitatory synaptic response, whereas 395 nm light decreases the conductance or drives it back toward the initial state, corresponding to an inhibitory response. This all-optical modulation behavior enables writing and erasing

to be realized by different illumination wavelengths without the need for additional electrical erasing operations. Compared with conventional optoelectronic memristors that require voltage-pulse-based resetting, this strategy can further simplify peripheral circuitry and improve the integration capability of optical neural-network hardware.

In addition, the device demonstrates information-resetting capability under positive bias. The voltage-dependent responses in Figure 3 indicate that different bias polarities strongly affect the retention and relaxation processes of light-induced states. When a positive bias is applied, the conductance state previously induced by optical stimulation can be rapidly driven back to its initial level, thereby realizing information clearing. This function is particularly important for continuous visual tasks, where practical vision systems need to refresh their internal states rapidly between different scenes to prevent residual historical information from causing recognition errors.



To further evaluate the application potential of the device in neuromorphic vision hardware, we constructed an arrayed optoelectronic memristive synaptic platform.

Figure 4 presents the pixel-level responses of the array devices, the optical writing/erasing processes, and their image reconstruction capability.

First, the array devices exhibit a relatively uniform baseline current distribution in the initial state. The two-dimensional current maps shown in Figure 4a and 4b reveal only small current fluctuations among different pixels, indicating good device uniformity across the array. Such uniform baseline currents are crucial for subsequent image writing and recognition, because excessive pixel-to-pixel variation would increase background noise and thus reduce the accuracy of information readout.

Subsequently, optical stimuli were applied to the array pixels and the corresponding response currents were recorded. The statistical results in Figure 4c show a clear distinction between the photoresponse current and the baseline current, indicating that the array pixels can effectively register optical input information. The photoresponse current distribution is concentrated in a higher-current region, whereas the baseline current distribution remains in a lower-current region, with a well-defined separation window between the two. These results demonstrate that the array is capable of pixel-level optical information storage.

Furthermore, Figure 4d illustrates the information writing and retention processes of the array under consecutive optical stimulation. In the initial state, the array remains in a low-conductance baseline state. After illumination, the currents of the stimulated pixels increase and form visible patterns. As time progresses, these patterns can still be retained with appreciable intensity, indicating that the conductance states induced by optical writing possess memory characteristics. In the subsequent stages, the stored patterns can either continue to evolve or remain preserved, reflecting the ability of the device to memorize temporally correlated optical inputs.

Figure 4e further demonstrates the all-optical writing, erasing, and rewriting capability of the device array. Specific patterns can be written into the array under 660 nm illumination; subsequently, the written patterns are erased by 395 nm illumination, and

the array returns to a state close to its initial condition. Upon re-illumination with 660 nm light, new patterns can be rewritten into the array. This process confirms that the array can not only realize optical writing, but also achieve non-contact optical erasing and pattern reconstruction. Compared with conventional electrically erased schemes, all-optical writing and erasing offer higher spatial selectivity and lower system complexity.

This array-level functionality of optical writing, optical erasing, and optical reconstruction is of substantial significance for neuromorphic vision systems. On the one hand, the array can directly convert spatial optical information into conductance distributions, thereby integrating sensing and storage within the same hardware platform. On the other hand, different illumination wavelengths can separately serve as writing and erasing signals, endowing the device with reconfigurable visual memory capability. Therefore, this array platform can serve as a fundamental building block for future all-optically controlled visual front ends, dynamic scene recorders, and low-power neuromorphic image-processing hardware.